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Review of research on autonomous wind farms and solar parks and their feasibility for commercial loads in hot regions

S.M. Shaahid*

Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

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ABSTRACT

In the wake of rising cost of oil and fears of its exhaustion coupled with increased pollution, the governments world-wide are deliberating and making huge strides to promote renewable energy sources such as solar–photovoltaic (solar–PV) and wind energy. Integration of diesel systems with hybrid wind–PV systems is pursued widely to reduce dependence on fossil-fuel produced energy and to reduce the release of carbon gases that cause global climate change. Literature indicates that commercial/residential buildings in the Kingdom of Saudi Arabia (KSA) consume an estimated 10–40% of the total electric energy generated. The study reviews research work carried out world-wide on wind farms and solar parks. The work also analyzes wind speed and solar radiation data of East-Coast (Dhahran), KSA, to assess the technical and economic potential of wind farm and solar PV park (hybrid wind–PV–diesel power systems) to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kWh). The monthly average wind speeds range from 3.3 to 5.6 m/s. The monthly average daily solar global radiation ranges from 3.61 to 7.96 kWh/m^2. The hybrid systems simulated consist of different combinations of 100 kW wind machines, PV panels, supplemented by diesel generators. NREL (and HOMER Energy's) HOMER software has been used to perform the techno-economic study. The simulation results indicate that for a hybrid system comprising of 100 kW wind capacity (37 m hub-height) and 40 kW of PV capacity together with 175 kW diesel system, the renewable energy fraction (with 0% annual capacity shortage) is 36% (24% wind + 12% PV). The cost of generating energy (COE, $/kWh) from this hybrid wind–PV–diesel system has been found to be 0.154 $/kWh (*assuming diesel fuel price of 0.1$/L*). The study exhibits that for a given hybrid configuration, the number of operational hours of diesel generators decreases with increase in wind farm and PV capacity. Attention has also been focused on wind/PV penetration, un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (relative to diesel-only situation) of different hybrid systems, cost break-down of wind–PV–diesel systems, COE of different hybrid systems, etc.

Contents

1. Introduction

The world is highly concerned of the harmful perils of global warming due to burning of depleting/carbon-rich/finite oil-based fossil fuels. It is believed that unless ways and means are explored to curb global warming, our life, our planet, and our children are all in danger. In the light of the above alarming issues, many countries

* Tel.: +966 03 860 3539; fax: +966 03 860 4281.
E-mail address: mshaahid@kfupm.edu.sa

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are embarking on utilization of renewable/clean sources of energy like solar and wind (as an option to mitigate future energy crisis and to overcome catastrophic effects of pollution). The last decade has brought with it rapid expansion in the use of renewable energy sources for displacement of oil-produced energy to reduce carbon emissions [1]. Furthermore, to comply with December 1997s Kyoto protocol on climate change, about 160 nations reached a first ever agreement to limit carbon emissions [2]. Also, there is increased interest in Saudi Arabia and other Gulf Countries in clean energy.

Solar and wind energy are non-depleting, site-dependent, non-polluting, and potential sources of sustainable energy options. Many countries (with average wind speeds in the range of 3–8 m/s) are pursuing the option of wind energy conversion system (WECS), in an effort to reduce their dependence on non-renewable fuels [3–6]. Wind is the world's fastest-growing energy source, with installed generating capacity increasing by an average of 20–25% annually for the last five years. Cumulative global wind energy capacity reached 93.849 MW in December 2007. The price of generating energy using wind machines has dropped considerably and is about 4–5 cents per kWh [7]. Also, presently thousands of PV deployments (with monthly average daily solar radiation in the range of 3–6 kWh/m^2) exist worldwide, providing power to remote applications [8–12]. By the end of 2006 the cumulative installed capacity of solar PV systems around the world reached more than 6500 MWp [13]. The United States, Japan, and Germany are leading the race in photovoltaic power development [14].

Stand-alone WECSs do not produce energy for considerable portion of the year because of their intermittent nature (associated with high cut-in speeds) [15]. Although solar energy is available in abundance, but PV-alone system needs a large storage system, and is an expensive option. Stand-alone diesel generator sets are expensive to operate and maintain especially at low load levels and they contribute in atmospheric degradation. The diesel generator efficiency drops when it operates at less than 40% of full load [16]. Use of PV–wind system alone (i.e. during night and when there is no wind) cannot satisfy load on a 24-h basis. In order to overcome this downtime, use of hybrid (wind–PV–diesel) systems has been recommended in the literature. Furthermore, wind and solar systems are expandable, additional capacity may be added as the need arises [17]. Seasonal variations of wind and solar resources are complementary to each other. The hybrid wind–solar–diesel based power generation is becoming a viable, cost-effective approach for electric supply especially for remotely located communities The prospects of hybrid systems is booming steadily and number of hybrid installations are deployed around the world [18–22].

Lot of research work is being carried out world-wide on feasibility/sizing of autonomous wind farms and solar parks. Borowy and Salameh [23,24] in their studies developed a methodology for calculation of the optimum size of a battery bank and the PV array for a stand-alone hybrid wind/PV system. The variability in the available energy from the wind/PV system makes it necessary to choose a right size of a battery bank so that the system will satisfy the load demand at any time. Hourly wind speed and irradiance data have been used to calculate the average power generated by a wind turbine and a PV module for every hour of a typical day in a month. A load of a typical house has been used as load demand of the hybrid system (Bergey 1.5 kW wind turbine, 53 W PV, 100 Ah battery capacity). The system operation is simulated for various combinations of PV array and battery sizes and the loss of power supply probability (LPSP) is calculated for each combination The choice of the optimum number of PV modules and batteries is based on the minimum cost of the system (for a given load and loss of power supply probability). It has been concluded that the optimum mix of PV modules and batteries depends on the particular site, load profile, and the desired reliability of the hybrid system

Hashem et al. [25] developed a computer approach for evaluating (to gain more insight of the system component sizes before they are built) the general performance of stand-alone wind/photovoltaic generating systems. Simple models for different system components were developed, integrated and used to predict the behavior of generating systems based on available wind/solar data. Simulation (using MATLAB) results for performance evaluation of a stand-alone generating system designed to supply the average power demand of a typical rural residential house located in south-central Montana. An electric water heater model is used as a dump load (excess energy is used to heat the water).

Diaf et al. [26] developed a methodology to perform the optimal sizing of an autonomous hybrid PV/wind system using an optimization model. The aim was to find the configuration which meets the desired system reliability requirements with the lowest value of levelised cost of energy (LCE). The methodology includes: proposing mathematical models (for characterizing PV module, wind generator and battery), optimizing the sizing of a system according to the loss of power supply probability (LPSP) and the LCE concepts. Several system configurations (by considering various types and size of the devices) which can meet the desired system reliability were obtained. The configuration with the lowest LCE gives the optimal choice. The methodology was applied to a PV/wind hybrid system to be installed at a remote Island. The study concludes that a hybrid system comprising of wind (600 W), PV (125 W) and battery storage (253 Ah) has been found to be optimal from both the economical and technical point of view (LPSP = 0, and LCE is lowest). The study also indicates that in order to reduce the energy excess, corresponding to the lowest LCE, the use of a third energy source (diesel) can be beneficial to the system. Diaf et al. [27] later applied the above methodology to find optimum size of system able to fulfill energy requirements (3 kWh/day) of a given load distribution for three sites located at Corsica island and analyzed the impact of different parameters on the system size. They concluded that: optimal configuration system size depends on the available wind and solar potential at a site, a 2 days storage capacity is best for the optimal configuration with the lowest LCE (for 3 kW/day load), the LCE decreases sharply with increase in load. Diaf et al. [28] also used the above methodology to define optimum dimensions of PV/wind/battery system for five sites in Corsica island and to study the impact of the renewable energy potential quality on the system size. The showed that LCE depends largely on the renewable energy potential quality. At high wind potential site, more than 40% of the total production energy is provided by the wind generator, while at low wind potential site, less than 20% of total production energy is generated by the wind generator.

Hongxing et al. [29] developed an optimal design/sizing model for designing stand-alone hybrid solar–wind systems employing battery banks based on the concepts of loss of power supply probability (LPSP) and annualized cost of system (ACS). The decision variables included in the optimization process are the PV module number, PV module slope angle, wind turbine number, wind turbine installation height and battery capacity. The proposed method has been applied to design a hybrid system to supply power for a telecommunication relay station along southeast coast of China. The results reported good complementary characteristics between the solar and wind energy, and the hybrid system turned out to be able to perform very well as expected throughout the year and the battery over-discharge situations seldom occurred (*strength of one source has been used to overcome the weakness of the other source*).Bitterlin [30] has made an attempt to explore the current practicalities of utilizing combined wind/PV (together with an energy storage system) power generation system for powering the remote cellular phone base stations (*total load* = 4 kW, i.e. 35 MWh/year). The storage (10 days autonomy; i.e. 1 MWh) is required to bridge the gap between the energy being available

and the instantaneous load consumption The study concludes that short-term autonomy is best provided by lead–acid batteries. The longer term intermittence of the wind demands a back-up power supply best provided by a diesel generator. The battery minimizes the start/run demand on the diesel engine, which in turn will minimize the required size of the battery storage capacity.

Yang et al. [31] developed a novel hybrid solar wind system optimization sizing model or tool (HSWSO) to optimize the capacity sizes of different components of hybrid solar–wind power generation systems employing a battery bank based on the concepts of loss of power supply probability (LPSP) and levelised cost of energy (LCE). The HSWSO model consists of three parts: the model of the hybrid system, the model of LPSP and the model of the LCE. The LPSP technique, which is considered to be the criteria for sizing, is the probability that an insufficient power supply results when the hybrid system is unable to satisfy the load demand. Several system configurations are obtained in terms of system power supply reliability requirement or system desired LPSP value by using LPSP model. The system with lowest LCE has been considered as economical optimal configuration. A case study has been simulated and reported to show the importance of the HSWSO model for sizing the capacities of wind turbines, PV panel and battery banks of a hybrid solar–wind renewable energy system. The optimal configurations of the hybrid system are obtained in terms of different desired system reliability requirements and the LCE.

Celik [32] presented a techno-economic analysis for different combinations of autonomous small photovoltaic(PV)/wind energy systems (i.e. PV only, wind only, hybrid PV–wind) in terms of performance-cost relationship. It has been shown an optimum combination of the hybrid photovoltaic–wind energy systems provides higher system performance than either of the single systems for the same system cost for every battery storage capacity analyzed. It is also shown that the magnitude of the battery storage capacity has an important bearing on the system performance of single PV and wind systems. Also, Celik [33] introduced a novel method for sizing and techno-economic optimization of an autonomous PV–wind hybrid energy system with battery storage. The method searches for an optimum combination of system autonomy and cost. Generally sizing methods are based on the worst renewable month scenario. It has been shown in this study that the worst month based scenarios lead to the least optimal systems in terms of techno-economics. Even though the worst months scenario provides a high level of autonomy (99%), the corresponding system cost turns out to be too high. However, it has been shown that the same level of autonomy (99%) could be obtained at less cost by the incorporating a third energy (auxiliary energy) supply. The study also suggests that the monthly solar radiation and wind speed distributions must be analyzed at the installation site.

Koutroulis et al. [34] presented a methodology for optimal sizing of stand-alone PV/wind-generator (PV/WG) systems. The purpose of the proposed methodology is to support the selection, among a list of commercially available system devices, the optimal number and type of units (*such as: the optimal number and type of PV modules* (*with tilt angle*), *wind generators* (*WG*) *and PV battery chargers, the installation height of the wind generators and the battery type and nominal capacity*) ensuring that the total system cost is minimized subject to the constraint that the load energy requirements completely covered resulting in zero load rejection. The major aspects in the design of PV and WG power generation systems are the reliable power supply of the consumer under varying atmospheric conditions and the corresponding total system cost. The proposed method has been applied to the design of a power generation system in order to supply a residential household. The simulation results verify that hybrid PV/WG systems feature lower system cost compared to the cases where the either exclusively WG or PV sources are used.

Tina et al. [35] presented a probabilistic approach to assess the performance of a HSWPS (hybrid solar–wind power system). Analytical expressions (using statistical approach convolving the probability density function of power generated) were developed to obtain the power generated. The hybrid system and the load models employed enable the study period to range from one year to one particular hour-of-day, thus allowing the inclusion of the time-value of energy as appropriate in economic assessments. The work has illustrated by means of a case study, that a good evaluation of the performance of a hybrid system can be obtained through a statistical approach alternative to time step simulations.

Muralikrishna and Lakshminarayana [36] developed a methodology (to determine the optimal size of the PV wind hybrid system, days of autonomy of battery, life of system, etc.) and evaluated the technical feasibility of PV–wind hybrid system in given range of rural load demand (with average wind speed of 5.1 m/s, solar insolation 5.89 kWh/m^2, load of 72 kWh/day). The influence of the deficiency of power supply probability (DPSP), relative excess power generated (REGP), energy to load ratio (ELR), fraction of PV and wind energy, and coverage of PV and wind energy against the system size and performance have been analyzed. The optimization of hybrid systems has been carried out by minimizing DPSP as well as REGP thereby reducing the cost of the system. They concluded that the PV wind hybrid system is economically viable when the grid line is 50 km away from the load point (and load is lower than 75 kW/day).

Ashok [37] discussed different system components (solar PV, wind, micro-hydro with diesel and battery backup) of hybrid energy system and developed a general model to find an optimal size of energy components/hardware for a typical rural community (with a population of over 600, daily energy demand of 317 kWh) minimizing the life cycle cost while ensuring reliable system operation for a given site/load.

Ding and Buckeridge [38] outlined the design considerations needed to produce a hybrid sustainable/balanced/stable energy system for night-time lighting of footpaths. Some of the considerations include: wind need to be used for night loads (wind based electricity is cheaper at windy sites), battery need to be used to store solar and wind energy produced during the day, cost benefit factor that has to be incorporated into the process, environmental benefits in terms of reduced pollution need to be quantified in the design, etc.

Lund [39] investigated/addressed the possibility and challenges of large-scale integration of renewable energy sources (RES, solar PV, wind, wave) into the electricity supply in Denmark. The analysis was carried by varying the electricity production from 0 to 100% (keeping excess electricity production to minimum) by using the computer model EnergyPLAN. The aim of the study was to take benefit of the different patterns in the fluctuations of different renewable sources and to identify optimal mixtures from technical point of view. The result illustrates the trend of increase of excess energy when the RES input is raised for wind power and PV as well as wave power. However, combinations of different RES reduces the increase in excess production.

Rajendra and Natarajan [40] presented a simulation software code for optimization (by employing iterative scheme) of a wind–PV integrated hybrid system based on deficiency of power probability (DPSP) relative excess power generated (REPG), unutilized energy probability (UEP), life cycle cost (LEC), levelised energy cost (LEC) and life cycle unit cost (LUC) of power generation with battery bank.

Mitchell et al. [41] described use of a model to demonstrate the main system design issues (such as fluctuating nature of the energy sources i.e. randomness) for renewable energy systems (stand-alone and grid connected) by using actual wind, solar and load

data. The model demonstrates the potential gains based on seasonal averages of wind, solar and load.

Orhan and Banu [42] showed the use of response surface methodology (RSM, collection of statistical and mathematical methods) in size optimization of an autonomous PV/wind integrated hybrid energy system with battery storage. The load considered in the study involves satisfaction of electricity consumption of the global system for mobile communication base station (at Izmir Institute of Technology Campus, Turkey). The work involved description of simulation model for hybrid energy system (& size level evaluation) analysis based on solar radiation and wind speed data, use of the simulation model to get regression model to predict solar radiation, wind speed and electricity consumption, use of RSM to optimize the regression model. The results obtained by RSM were confirmed using loss of load probability analysis.

Ekren et al. [43] also showed an optimum sizing procedure of autonomous PV/wind hybrid energy system with battery storage and a break-even analysis of this system and extension of transmission line. Besides, evaluation of a hybrid energy system and extension of the transmission line, the break-even analysis has shown a way to be able to decide on the profitable two alternative systems. The result shows that if the distance between national electricity network and the GSM base station location (where the hybrid energy system is assumed to be installed) is at a distance more than 4817 m, the installation of hybrid energy system is more economical than the electricity network. Saheb et al. [44] reported results of the technical-economic optimization study of photovoltaic/wind/diesel hybrid with battery storage for remote consumers of different sites of Algeria (with lower cost of energy). Matlab/Simulink V 6.5 was used for simulations and the results indicate that hybrid system (in view of enhance reliability as compared to PV or wind alone case) is the best option. Razak et al. [45] discussed the option of optimization of hybrid (solar/wind/hydro/diesel/battery) system in the context of minimizing the excess energy and cost of energy (by considering three types of demand loads). The authors highlight that generally the problem of maximum usage of component capacity is neglected (many a times 50% excess energy is produced while providing to meet the load demand).

Dalton et al. [46] assessed the feasibility of renewable energy supply (RES) for a stand-alone supply large hotel (over 100 beds, annual energy consumption of 5.5 GWh, peak load of 966 kW, located in coastal area, Queensland, Australia) based on net present cost (NPC), renewable fraction (RF) and payback time. The study used software tool HOMER in order to compare diesel-generator-only, RES-only and RES/diesel hybrid technologies. The monthly average wind speed has been found to vary between 4 and 6 m/s. The solar irradiance has been found to vary between 3.4 kWh/m^2/day and 6 kWh/m^2/day. The modeling results demonstrate that RES, in principle, has the potential to adequately and reliably meet power demand for the stand-alone large hotel. However, a hybrid diesel/RES configuration provides the lowest NPC result with RF of 76%. The optimum hybrid configuration consisted consisted of a Vesta WECS (1.8 MW), 600 kW diesel generator. In comparison to the diesel generator-only configuration, NPC is reduced by 50% and Greenhouse Gas (GHC) emissions by 65%. The pay-back time of the hybrid RES scenario is 4–3 years. Dalton et al. [47] also carried out the analysis (on HOMER) to compare grid-only, RES-only and RES/grid hybrid configurations. The optimization modeling results demonstrate that grid/RES hybrid configuration is comparable with the grid-only supply and resulted in a RF of 73%, a pay-back period of 14 years, and a reduction in Greenhouse Gas (GHC) emissions of 65%.

Bakos and Tsagas [48] reported the technical feasibility and economic viability of a hybrid solar/wind grid connected system for electrical and thermal energy production, covering the energy demand of a typical residence (with annual energy demand of 21,088 kWh) in the city of Xanthi (Greece). The hybrid system comprised of solar thermal collector (3.5 m^2 aperture area) and wind machine (2.2 kW rated power). The energy output was estimated by simulation program based on the Monte Carlo Method. The auxiliary energy source (to provide power during cloudy and low wind periods) is natural gas. The economic analysis of the proposed hybrid solar/wind system has been performed using the life cycle savings (LCS) method and the pay back period has been found to be 12 years. Jose et al. [49] designed a PV–wind–diesel system for two different load profiles (farm load of 40.9 kWh/day, high load of 120 kWh/day) by simultaneously minimizing the total cost and pollutant emissions (important environmental issue). For each load profile, several possible solutions have been achieved facilitating the selection of best practical option.

Aydogan et al. [50] studied a system which produced electrical energy from both solar radiation (solar cells) and wind energy (in Izmar, Turkey). It has been found that the combined (wind + solar) system supports each other (solar or wind) when one of them produces energy insufficiently (i.e. load demand cannot be fulfilled by solar during no-sun periods and wind cannot meet constant load demands due to its fluctuating nature). Recayi et al. [51] designed and implemented a novel laboratory set-up at the University of Northern Iowa as an instructional resource for teaching electrical power system and renewable energy concept. The set-up consists of a photo-voltaic solar-cell array, a mast mounted wind generator, lead–acid storage batteries, an inverter unit to convert DC power to AC power, electrical lighting loads and electrical heating loads, several fuse and junction boxes and associated wiring, and test instruments for measuring voltages, currents, power factors, etc. The hybrid solar–wind power generating system is extensively used to illustrate electrical concepts.

Rachid et al. [52] presented a methodology for sizing optimization of a stand-alone hybrid wind/PV energy system. The approach makes use of deterministic algorithm to minimize the life cycle cost (objective function) of the system while guaranteeing the availability of the energy. Firstly, the mathematical models of the principal elements are presented. Then, the algorithm is implemented to minimize the objective function. The study highlights that the optimum number of wind turbine, PV panels and batteries depend on the particular site, load profile and the specifications and the related costs of each component of the hybrid system.

Kellog et al. [53] investigated the application of wind-alone, solar-alone, and hybrid wind/PV generation to meet a residential load. A simple numerical algorithm, taking into account economic factors, was developed for finding the optimum component size for the three configurations to supply a known load pattern at a given site. As an example, the algorithm was used to find the generation and storage capacity needed to supply hourly average load profile of a typical ranch/remote home located in Montana.

Karaki et al. [54] presented the development of a general probabilistic approach to model and simulate the operation of an autonomous solar–wind energy conversion system composed of several wind turbines (wind farm), several PV modules (solar park), and a battery storage feeding a load. The wind turbines and PV modules may be identical or of different types. The model takes into consideration outages due to the primary energy fluctuations and hardware failure. A methodology was presented to combine this hybrid model to a load model in order to assess the expected energy supplied to a load with or without battery storage. Procedures based on simple probability theorems for building the wind and solar PV models were considered. The combination of the two models to obtain a hybrid system was carried using convolution. Also, the methodology allows the determination of the upper limit on storage batteries required to cover a given load taking into consideration the charging discharging of the batteries

The Kingdom is not only a major producer, but also a major consumer of energy. The exponentially growing demands of energy due to fast industrial development in the Kingdom have imposed tremendous pressure on the government and the electric utilities to provide the required energy. The number of consumers grew from 300,000 in early 1970 to about 4.2 million in 2003 [55]. The installed generating capacity of the power plants reached more than 30,000 MW in 2003 [55]. The demand for electricity is expected to reach about 55,000 MW by 2020. In view of the increasing demands of energy, renewable energy sources (like solar, wind, etc.) need to be exploited and promoted in the Kingdom. The retrofitting of wind turbines and PV systems along with the existing diesel stations may result in reduced fuel transport/storage/consumption, lower diesel emissions, and possibly longer engine life. Since KSA is endowed with ample solar radiation intensity and appreciable wind regime, a substantial portion of its energy demands may be captured from solar and wind energy. Also investments in mobilization of wind and solar power can stimulate the local economy (in a long run) by making use of available local indigenous/indispensable resources. Additionally, the use of renewable energy reduces CO_2 emissions which is the principal cause of global warming [56,57].

The research on feasibility of renewable/sustainable energy systems at Dhahran, has been the subject matter of several earlier studies [58–62]. In the present study, research work carried out world-wide on wind farms and solar parks has been reviewed. Also, in the present work, wind-speed data (of the year 1997) and solar radiation data (long term average of the period 1986–1993) of Dhahran (26°32′N, 50°13′E) has been analyzed to assess the technical and economic potential of autonomous wind farm and solar PV park (hybrid wind–PV–diesel power systems) to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kWh). The hybrid systems simulated consist of different combinations of 100 kW wind machines, PV panels, supplemented by diesel generators. The study evaluates the feasibility of utilizing wind–PV energy to meet the load requirements of a typical commercial building in conjunction with the diesel generators. Specifically, the merit of hybrid wind–PV–diesel system has been evaluated with regards to its size, operational requirements, cost, etc. National Renewable Energy Laboratory (NREL) and HOMER Energy's HOMER software has been used to perform the techno-economic feasibility. HOMER is a computer-model that facilitates design of stand-alone electric power systems [63]. The investigation places emphasis on the impact of wind/PV penetration on: energy production, number of operational hours of diesel gensets for a given hybrid configuration, etc. Attention has also been focused on un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (relative to diesel-only scenario) of different hybrid systems, cost of wind–PV–diesel systems, COE of different hybrid systems, etc.

2. Background information

Climatic conditions dictate the availability and magnitude of wind and solar energy at a site. Dhahran is located on the eastern coastal plain of Saudi Arabia and is nearly 10 km inland from the Arabian Gulf Coast. Although it is in the vicinity of the coast, but is situated in a desert environment. Two distinct seasons are noticed in this region: a very hot season (May–October) and a cold season (November–April). Monthly mean temperatures reach close to 37 °C for hot months and in cooler months the mean temperatures drop by about 20 °C as compared to the hot months. The relative humidity exhibits a large diurnal cycle on the order of 60% round the year. Typical long-term annual mean precipitation is about 80 mm. The winds blow from 270° to 360° direction range

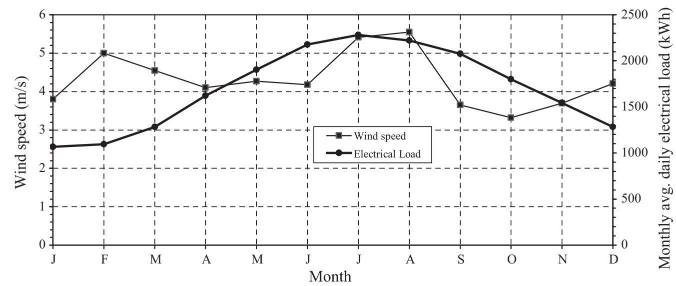


Fig. 1. Monthly average wind speed and monthly average daily commercial load.

(north to north-westerly winds) for most of the time during the year [64,65].

3. Wind and solar radiation data and dispatch strategy of hybrid system

An earlier study on WECSs at Dhahran has analyzed long-term (1986–1997) wind speed data [66]. In the present study, wind-speed data of the year 1997 has been considered as a representative year for assessing the performance of hybrid wind–diesel systems using HOMER software. The monthly average wind speeds for Dhahran of the year 1997 are presented in Fig. 1. Wind speeds are generally higher in summer months (May–August) as compared to other months. This indicates that a WECS would produce appreciably more energy during summer months as compared to the other months (*this is a welcome/favorable characteristic because the load is high in summer in this part of the world*). The monthly behavior of wind speed matches the higher electrical load requirements during summer period in Saudi Arabia. The data also indicates that there is noticeable variation of monthly average wind speed from one month to another month. These variations indicate that the monthly energy output from WECS would be subjected to considerable differences. The monthly average wind speeds during 1997 have been found to range from 3.3 to 5.6 m/s. The yearly average wind speed of 1997 is 4.31 m/s at 10 m height. The monthly average wind speeds corresponding to the year 1997 at different hub-heights (by using 1/7th power law) are presented in Fig. 2. Wind is faster, less turbulent and yields more energy at 30 m or more heights above the ground. With increase in height from 10 m to 50 m, the wind speed increases by about 26%. The raw daily wind speed data of the year 1997 is shown in Fig. 3. The cumulative frequency distribution of wind speed is illustrated in Fig. 4. The calculations of wind energy (in HOMER) are made by matching the power–wind speed characteristics of commercial wind machines (CWMs) with the hub-height wind speed data. The characteristics of the 100 kW CWMs considered in this study are presented in Table 1. The technical and performance characteristics of diesel

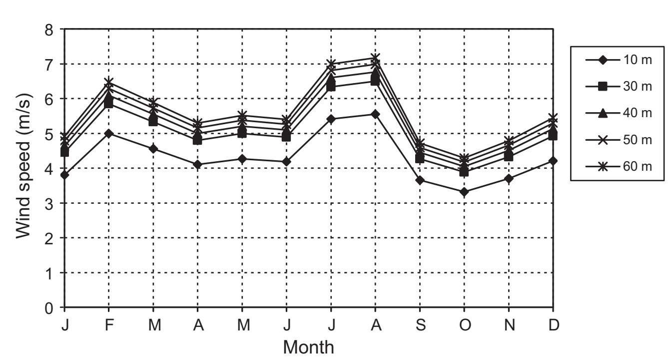


Fig. 2. Monthly average wind speed at different hub-heights.

Table 1
Power–wind characteristics of 100 kW commercial wind machine.

Wind machine model	Rated power, Rp (kW)	Rated speed, Vs (m/s)	Cut-in speed, Vci (m/s)	Cut-out speed, Vco (m/s)	Rotor diameter (m)	Hub height (m)
NW100	100	15.0	3	25	21	37

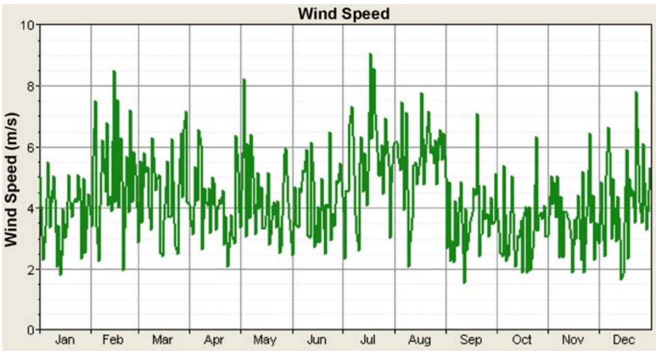


Fig. 3. Daily wind speed data for one complete year.

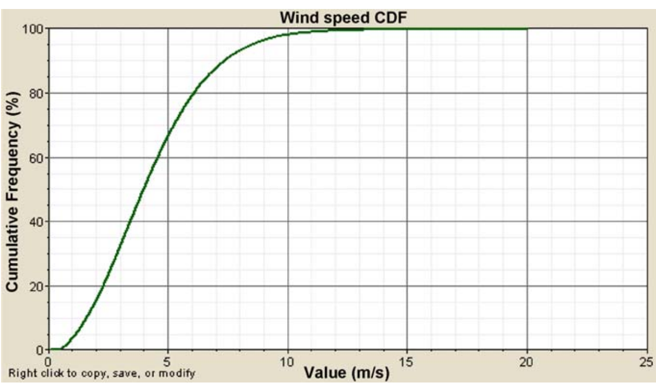


Fig. 4. Cumulative frequency distribution of wind speed.

generators assumed in the study are tabulated in Table 2. The power-curve of the 100 kW wind machine is shown in Fig. 5. Today's best wind machines can achieve an overall efficiency of about 35% [67,68]. However it may be mentioned that further technological milestones, may change the scenario and pave way for more wide-spread use of PV systems [69].

Long term monthly average daily global solar radiation data (of the period 1986–1993) of Dhahran is plotted in Fig. 6. The solar

Table 2
Technical data and study assumptions of PV and diesel units.

Description	Data
PV	
Life time	25 years
Operation and maintenance cost	0 US$/year
Diesel generator units	
Rated power of diesel unit 1 [D1]	120 kW
Minimum allowed power (min. load ratio)	30% of rated power
No load fuel consumption	39.6 L/h
Full load fuel consumption	10.09 L/h
Rated power of diesel unit 2 [D2]	55 kW
Minimum allowed power (min. load ratio)	30% of rated power
No load fuel consumption	18.15 L/h
Full load fuel consumption	4.63 L/h
Dispatch/operating strategy	Multiple diesel load following
Spinning reserve	
Additional online diesel capacity (to shield against increases in the load or decreases in the wind power output)	10% of the load

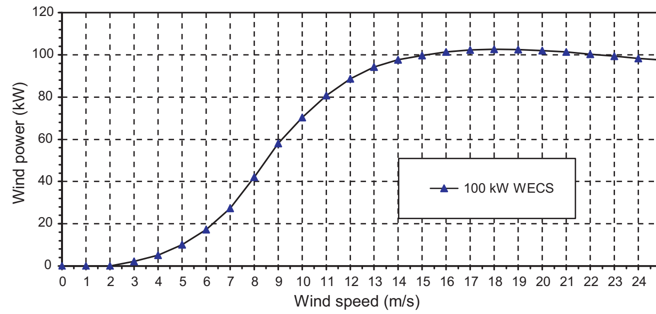


Fig. 5. Power curve of commercial 100 kW wind machine.

radiation is high during the summer months (May–August) as compared to other months. The yearly average daily value of the solar radiation is 5.84 kWh/m^2. The above long-term monthly average daily data has been used for simulations in HOMER. Today's best PV systems can achieve an overall efficiency of about 12% [10]. These lower efficiency values may not make this alternative attractive at the moment. However, technological breakthroughs, may change the scenario and pave way for more wide-spread use of PV systems [69].

In general, the cut-in wind speed (speed at which wind machine starts producing useable energy) of most of the CWMs ranges from 3 to 4 m/s [58]. The wind duration analysis indicates that the wind speeds are less than 3 m/s for about 40% (at 10 m height) of the time during the year as shown in Fig. 4. This implies that a stand-alone WECS if installed at Dhahran will not produce any energy for about 40% of the time (during the year) and hence cannot meet the required load distribution on a continuous basis. In this regard (to cope-up with the down-time of WECS), integration of WECS with PV and diesel systems can meet the required load distribution on a 24-h basis.

The hybrid wind–PV–diesel system configuration is shown in Fig. 7. The dispatch strategy of the hybrid system is as follows: in normal operation, WECS and PV feed the load demand. The diesel gensets are operated (brought-on-line/engaged) at times when WECS and PV fail to satisfy the load.

4. Results and discussion

An important driving element of any power generating system is load. Load influences the power system design markedly.

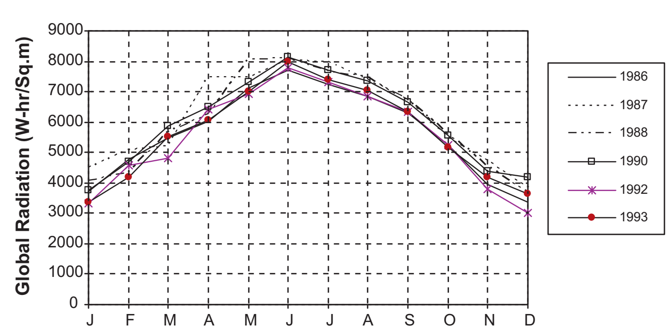


Fig. 6. Monthly average daily global radiation at Dhahran.

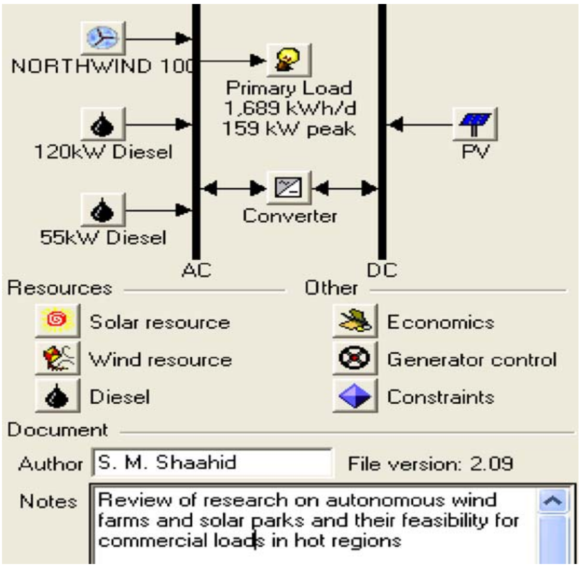


Fig. 7. Schematic of hybrid wind–PV–diesel power system.

The present work focuses attention on commercial loads. As a case study and as a representation of commercial buildings, the measured annual average electric energy consumption of a typical air-conditioned supermarket (located in Dhahran, floor area = 945 m^2) has been considered as yearly load (620,000 kWh; maximum load = 159 kW) in the present study [70]. The monthly average daily electrical energy consumption is shown in Fig. 1. As depicted in Fig. 1, the load seems to peak during June to September. The peak requirements of the load dictate the system size. This load could also be a representation of many remotely located commercial buildings which lack access to the utility grid (even today, there are many communities living or dwelling in small pockets in remote locations of KSA). The KSA's area is large, with large number of settlements (far from electric grids) scattered all over the Kingdom. The supply of electricity to these remote locations through diesel generators alone or by connecting into the nearest grid could be an expensive option. The retrofitting of wind turbines and solar PV systems along with the diesel systems may result in reduced fuel transport/storage/consumption, lower diesel emissions, fewer diesel spills, and possibly longer engine life. The raw electrical load data for a complete year is presented in Fig. 8.

In the present study, the selection and sizing of components of hybrid power system has been done using NREL's (and HOMER Energy's) HOMER software. HOMER is a hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical loads (e.g. load data), renewable resources

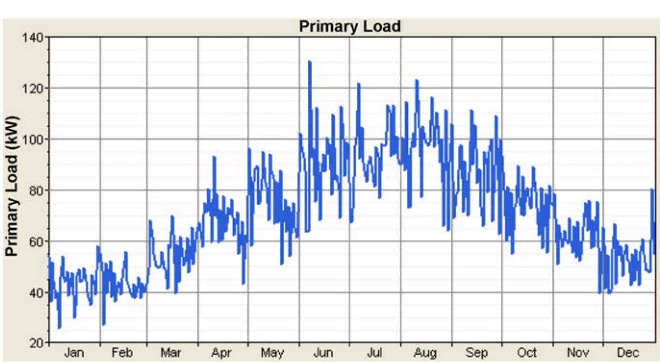


Fig. 8. Daily average load (kW) for a complete year.

(e.g. solar radiation data, wind speed data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER designs a optimal power system to serve the desired loads. It is an optimization model which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. The software also performs automatic sensitivity analysis to account for the sensitivity of the hybrid system design to key parameters, such as the resource availability or component costs [63].

The hybrid systems simulated consist of different combinations of 100 kW wind machines (clustered into wind farms of different capacities), PV panels supplemented by diesel generators. The study explores a suitable mix of key parameters such as: wind farm capacity, PV array power (kWp), and diesel capacity to match the pre-defined load (with 0% capacity shortage). As a rule of thumb, diesel generators are generally sized to meet the peak demand of the power. The peak demand in the present case-study is 159 kW as depicted in Fig. 7. In this regard, two diesel generator sets with a combined power of 175 kW (to cover peak load and to cover spinning reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the technical and economic analysis of the hybrid systems. The capacities of the two diesel gensets (D1, D2) are 120 kW and 55 kW respectively. The spinning reserve is surplus electrical generation capacity (over and above that required to cover the load) that is instantly available to cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations have been made by considering different combinations of wind farm capacities and PV capacities. The number of geographically separated wind turbines (100 kW) has been allowed to vary from 0 to 3. The PV capacity has been allowed to vary from 0 kW to 120 kW. The study assumptions made for making simulations on HOMER are furnished in Tables 1 and 2. The results of simulations (*for diesel price of* 0.1 US$/L) for different scenarios (*diesel only*, *wind–diesel with 37 m hub-height for WECS*, *PV–diesel*, *wind–PV–diesel with 37 m hub-height for WECS*) are summarized in Table 3. It can be noticed from these results that in general the renewable energy fraction (wind + PV) has varied from 0 to 53% (i.e. 21% wind + 32% PV). The level of renewable energy penetration in hybrid systems deployed around the world is generally in the range of 11–35% [15]. A trade-off need to be established between different feasible options. The COE from a hybrid wind–PV–diesel system (100 kW WECS, 40 kW, 175 kW diesel system, 0% annual capacity shortage) with 36% (24% wind + 12% PV) renewable penetration has been found to be is 0.154 US$/kWh as shown in Table 3. It can be depicted from Table 3, that COE increases with increase in penetration of wind/PV.

It is also evident from Table 3, that as penetration of wind–PV increases, the operational hours of diesel generators decrease which eventually reduce emission of green house gases. It can be noticed that for diesel-only situation, the operational hours of the two diesel units are 6801 and 2534 respectively. However, for hybrid wind–PV–diesel system (100 kW WECS, 40 kW, 175 kW diesel system, 0% annual capacity shortage, as shown in Fig. 7) with 36% (24% wind + 12% PV) renewable penetration, the operational hours of the two diesel units are 4989 and 3823 respectively. This clearly reflects that operational hours of the bigger diesel generator (D1, 120 kW) of hybrid wind–PV–diesel (36% renewable energy penetration) system decrease by 27% as compared to diesel-only (zero % wind/PV energy) situation. This indicates that with introduction of wind/PV systems, load on the first diesel generator has decreased substantially.

For a given hybrid system with 100 kW WECS (with 37 m hub-height for WECS) + PV capacity of 40 kW (together with 175 kW

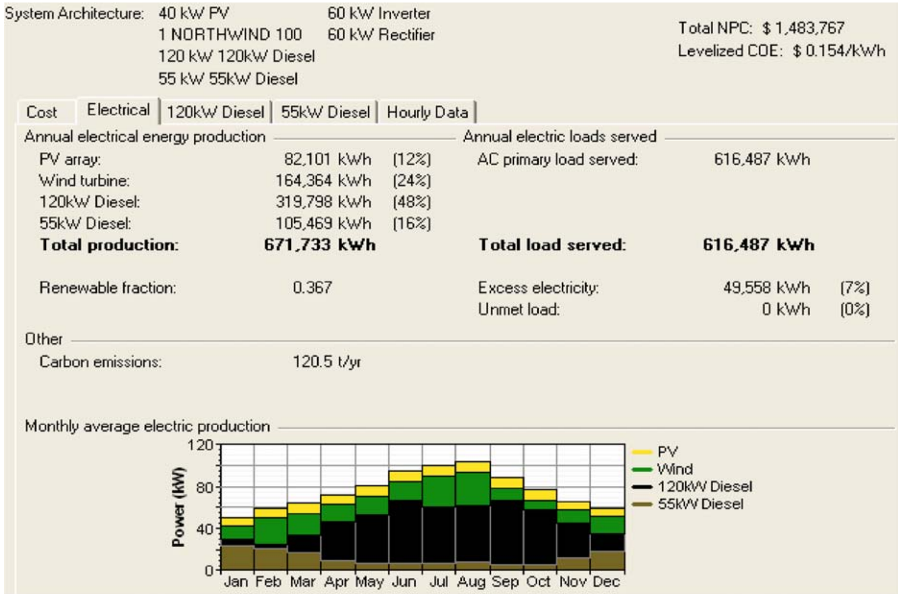
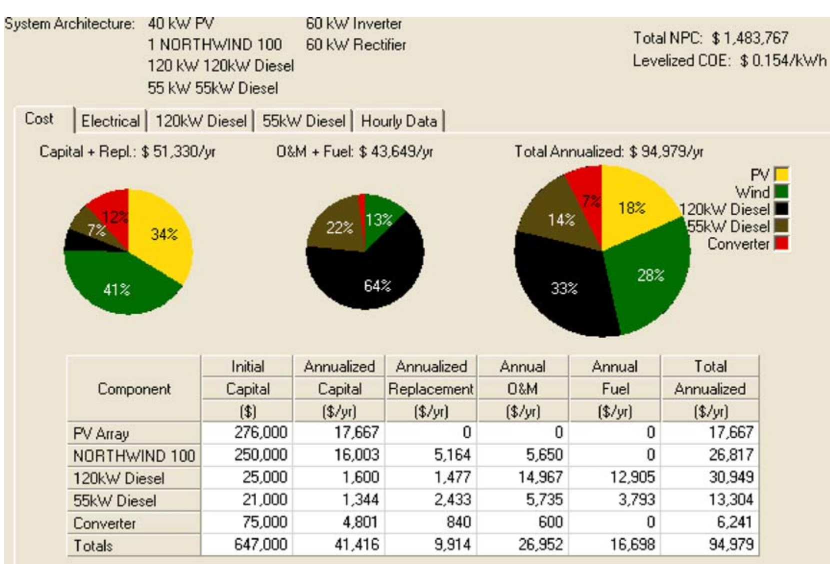


Fig. 9. Power generated by wind, photovoltaic and diesel systems.

diesel system), the information related to energy generated by wind machines, PV and diesel systems, excess electricity, unmet load (kWh), capacity shortage (kWh) and the cost break-down of wind–PV–diesel power systems is presented in Figs. 9 and 10. It can be seen from Fig. 9 that with the above system configuration, unmet load is zero kWh and excess energy of about 7% is generated. It should be mentioned that lesser the excess energy, better is the economy of the hybrid system. Fig. 9 also indicates that monthly average hybrid wind–PV–diesel generated power is high during summer months (May–August) as compared to other months. This is a favorable characteristic because electricity demand is high during the summer months in KSA. HOMER hybrid model indicates that the total initial capital cost of the hybrid system (100 kW WECS, 40 kW PV, 175 kW diesel system) is US$ 647,000 while the Net Present Cost (NPC) is US$ 1,483,767 (Figs. 9 and 10). It can be noticed from (Fig. 10) that the initial capital cost of wind + PV systems is about 75% of the total initial capital cost. This highlights that initial cost of hybrid wind + PV system is predominant. However, the annual operation and maintenance cost of wind–PV system, is very less as compared to the O & M + fuel cost of the diesel system.

The percentage of fuel savings by using hybrid system (100 kW WECS, 40 kW PV, 175 kW diesel system) as compared to the diesel only situation is about 27% as shown in Table 3. Moreover, percentage fuel savings increases by increasing the renewable energy capacity. It has also been observed that the carbon emissions for diesel-only are 165 tons/year. However, with wind–PV–diesel hybrid system (100 kW WECS, 40 kW PV, 175 kW diesel system, with 37 m hub-height for WECS) the carbon emissions are 121 tons/year (Fig. 9). This reflects that the percentage decrease in carbon emissions with 36% renewable penetration is about 27% as compared to diesel-only (zero % wind–PV energy) case. This implies about 44 tons/year of carbon emissions can be voided entering into the local atmosphere with 36% (24% wind + 12% PV) renewable energy penetration.



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	276,000	17,667	0	0	0	17,667
NORTHWIND 100	250,000	16,003	5,164	5,650	0	26,817
120kW Diesel	25,000	1,600	1,477	14,967	12,905	30,949
55kW Diesel	21,000	1,344	2,433	5,735	3,793	13,304
Converter	75,000	4,801	840	600	0	6,241
Totals	647,000	41,416	9,914	26,952	16,698	94,979

Fig. 10. Cost of wind, photovoltaic and diesel power systems.

Table 3
Number of operational hours of diesel generators, wind and PV penetration, un-met load, excess energy, annual diesel fuel consumption, cost of energy of hybrid wind–PV–diesel systems (*for given wind/PV–diesel* capacity, based on diesel price of 0.1 US$/L).

Hybrid system (kW)			Operational hours of the two diesel generators		Renewable energy fraction (% of load)		Un-met load (kWh)	Excess energy (%)	Carbon emissions (tons/year)	Annual diesel fuel consumption (L/year)	Cost of energy, COE ($/kWh)
Diesel (kW)	Wind (kW)	PV (kW)	D1 120 kW	D2 55 kW	Wind	PV					
175	0	0	6801	2534	0	0	0	0	165	228,024	0.087
175	100	0	5749	3268	25	0	0	4	135	186,431	0.121
	200	0	4858	3654	45	0	0	16	116	160,450	0.156
	300	0	4295	3545	58	0	0	27	103	142,009	0.193
	0	40	6032	3126	0	13	0	0	148	204,490	0.130
	0	80	5341	3623	0	25	0	3	133	185,982	0.143
	0	120	4868	3809	0	35	0	10	126	174,095	0.168

Table 4
Effect of PV penetration on a given hybrid wind–diesel (100 kW WECS, 175 kW diesel) system.

Hybrid system (kW)			Operational hours of the two diesel generators		Renewable energy fraction (% of load)		Un-met load (kWh)	Excess energy (%)	Carbon emissions (tons/year)	Annual diesel fuel consumption (L/year)	Cost of energy, COE ($/kWh)
Diesel (kW)	Wind (kW)	PV (kW)	D1 120 kW	D2 55 kW	Wind	PV					
175	100	0	5749	3268	25	0	0	4	135	186,431	0.121
		40	4989	3823	24	12	0	7	121	166,976	0.154
		80	4392	4094	23	23	0	12	110	152,116	0.198
		120	4003	3912	21	32	0	18	103	142,819	0.203

The location being blessed with abundant monthly average daily global solar radiation intensity (3.61–7.96 kWh/m^2) is a prospective candidate for deployment of PV power systems. So, as a final remark, attempt has been made to address the impact of incorporation/penetration of PV on a given hybrid wind–diesel system in terms of fuel savings, total diesel run time, excess energy generation, etc. The simulation results are furnished in Table 4. It can be seen from Table 4, that presence of PV results in further saving in diesel fuel, decrease in operation times of diesel gensets, and decrease in carbon emissions. However, increase in PV penetration results in increase in COE. As mentioned earlier, technological breakthroughs, may change the scenario.

5. Conclusions and recommendations

The present has reviewed research work carried out world-wide on wind farms and solar parks. The work also analyzed wind speed and solar radiation data of East-Coast (Dhahran), KSA, to assess the techno-economic potential of wind farm and solar PV park (hybrid wind–PV–diesel power systems) to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kWh) of Saudi Arabia. Specifically, the merit of hybrid wind–PV–diesel systems has been evaluated with regards to its size, operational requirement, cost, etc.

The study indicates that for a hybrid system comprising of 100 kW wind farm capacity (37 m hub-height), 40 kW of PV capacity together with 175 kW diesel system (D1:120 kW, D2: 55 kW), the renewable energy fraction (with 0% annual capacity shortage) is 36% (24% wind + 12% PV). The cost of generating energy (COE) from this hybrid wind–PV–diesel system has been found to be 0.154 US$/kWh (*assuming a diesel fuel price of 0.1$/L*). The total Net Present Cost (NPC) of the above hybrid system has been found to be US$ 1,483,767. Also for this configuration, the unmet load is zero kWh. The percentage fuel savings by using the above hybrid system has been found to be about 27% relative to diesel-only situation. Additionally, the reduction in carbon emissions is about 27% relative to zero % wind–PV case. The study also indicates that the operational hours of diesel generators decrease with increase in wind farm capacity and solar PV park capacity. More importantly, with use of the above hybrid system, about 44 tons/year of carbon emissions can be avoided into the local atmosphere. Attempt has also been made to address the effect of PV penetration on hybrid wind–diesel energy generation. It has been noticed that presence of PV further decreases fuel consumption, reduces carbon emissions and decreases operation time of diesel generators.

The observations of this work can be employed as a reference/platform/benchmark to carry out economic feasibility of wind farm and solar PV park (hybrid wind–PV–diesel power systems) for other locations having similar climatic/load conditions.

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